Localized emitters close to nano-bowties: insight via conformal transformation

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Localized Emitters Close to Nano-Bowties: Insight via Conformal Transformation

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***Abstract* – Investigating the near-field interaction of a dipole source such as a single quantum-dot with nearby dimers such as bowties is a challenging problem because of the lack of analytical models and the difficulty to perform the experiment. We tackle this problem here by using a conformal transformation. We show how, in the electrostatic approximation, the bowtie and point dipole source can be transformed into the analytically solvable configuration of a periodic metal-insulator-metal and point dipole source configuration. The analytical solutions are validated with full-wave simulations.**

I. INTRODUCTION

The study of the complex interaction between localized surface plasmons supported by metallic nanoparticles and quantum emitters is undertaking a great deal of both theoretical and experimental research [1]–[3]. Simple analytical solutions exist for canonical situations like a point dipole near a spherical nanoparticle, which have facilitated the design of experiments so far. However, the catalogue of possible nanoparticle shapes has expanded recently dramatically as a result of the new nanofabrication techniques [4], [5] and there is a need for analytical solutions that could give a fast yet accurate physical insight on the non-canonical situation.

Among the wide range of shapes available nowadays, triangles have become widely used in pairs (the so-called bowtie) given their strong field intensity at the apex or gap and larger operation bandwidth than nano-dipoles [6]. Hence, we focus here on such system and study the behavior of the localized surface plasmons and the coupling of them with a localized emitter from a transformation optics perspective. This theoretical approach has been successfully applied to other nanosystems like nanowires, crescent-shaped cylinders and nanospheres [7]–[10] , and was used in the past for the resolution of complex microwave problems transforming them to a coordinate system with simpler solution [11], [12].

II. FROM BOWTIE TO PERIODIC METAL-INSULATOR-METAL CONFIGURATION

The system under study, whose analytical solution cannot be found in the literature, is sketched in Fig. 1(a). It is composed of a silver bowtie illuminated by a point dipole placed 1 nm away. For this work, the total length of the bowtie l' is 20 nm, the arm angle θ' = 15 deg and the gap between arms (see inset in Fig. 1(a)) varies from 0.3 to 2.7 nm. The material property of silver is taken from Palik's experimental data in all the derivations and the Comsol simulations. If we apply the transformation $z' = \ln(z)$, the configuration is transformed to the system shown in Fig. 1(b) [13]. This periodic metal-insulator-metal problem can be solved analytically under the electrostatic approximation. Since the system has a certain length, it can be decomposed in a set of modes with discrete angular momentum, n [10]. The resonant condition governing the discrete modes is:

$$\begin{aligned}&(\varepsilon_{metal}(\omega)-1)^4\left[e^{2n\pi(3d_1+6d_2+2d_3/(L_1+L_2))}+e^{2n\pi(d_1+4(d_2+d_3)/(L_1+L_2))}\right]+\\&+(\varepsilon_{metal}(\omega)+1)^4\left[e^{2n\pi(d_1+4d_2+2d_3/(L_1+L_2))}+e^{2n\pi(3d_1+6d_2+4d_3/(L_1+L_2))}\right]-\\&-2\left(\varepsilon_{metal}(\omega)^2-1\right)^2\left[e^{6n\pi(d_1+2d_2+d_3/(L_1+L_2))}+e^{2n\pi(2d_1+5d_2+2d_3/(L_1+L_2))}+e^{2n\pi(d_1+4d_2+3d_3/(L_1+L_2))}+e^{2n\pi(2d_1+5d_2+4d_3/(L_1+L_2))}-2e^{2n\pi(2d_1+5d_2+3d_3/(L_1+L_2))}\right]-\\&-8\varepsilon_{metal}(\omega)^2\left[e^{2n\pi(2d_1+5d_2+3d_3/(L_1+L_2))}\right]=0\end{aligned}\tag{1}$$

If the arms were touching at a single point, the transformed system would be infinite in length, and thus, the modes would no longer be discrete modes and a continuous surface plasmon polariton would be supported instead [10]. Therefore, the behavior of the original bowtie surface plasmons and their coupling with the localized emitter can be deduced in the transformed system with closed-form expressions.

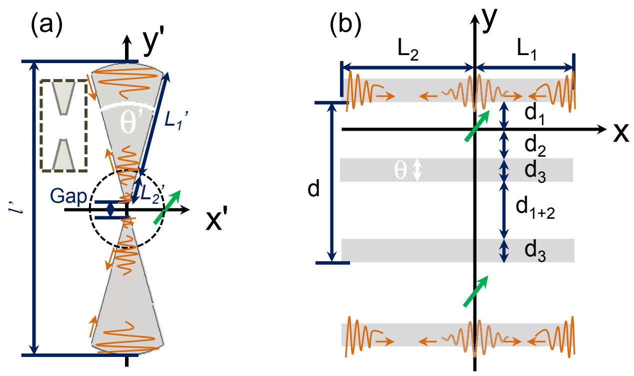

Fig. 1. (a) Configuration under study: an emitter coupled to the localized surface plasmons supported by a bowtie. (b) The multislab problem that arises when the transformation *z*' = ln(*z*) is applied to (a).

III. Analytical and Numerical Results

The absorption cross section spectra computed analytically for different gap sizes and for a parallel and perpendicular dipole are plotted in Fig. 2(a,d). To facilitate the comparison with the full-wave simulations carried out with Comsol (Fig. 2(c,f)), specific gap values are plotted in Fig. 2(b, e). For the vertical polarization, we can see an absorption peak going from ~635 nm to ~520 nm as the gap is increased. This peak is associated to the localized surface plasmon of angular momentum n = 1 with a field pattern in the transformed space with anti-nodes at both ends and a node at the center. The second peak that emerges around ~450 nm for small gap sizes and also undergoes a blueshift as the gap size increases, corresponds to the next localized surface plasmon (n = 2). This second mode has three anti-nodes (two at both ends of the metallic slab and the third one at the centre) and two nodes. For the horizontal polarization, the fundamental and second mode appears at ~472 nm and ~417 nm, respectively, and they also show a blueshift with the gap size. By looking at the transformed system, the blueshift can be explained in very simple terms. An increase of the bowtie gap size is transformed into a decrease of the slab length. Hence, the resonant condition (1) is satisfied for shorter wavelength.

The comparison between the analytical calculations and the simulations show good agreement. The discrepancies of the amplitude arise from the assumption that there is no radiative damping in the transformed space (i.e., there is no radiation at the two ends of the slab).

VI. Conclusion

The interaction between a nanobowtie and a localized dipole parallel and perpendicular to the dimer's axis has been studied from a conformal transformation perspective. This approach provides physical insight on the problem and enables predicting the electromagnetic response of the system without the need of computational intensive simulations that have been, however, performed to validate the analytical work. This work holds promise for the rapid emerging field of bionanotechnology and quantum-plasmonics.

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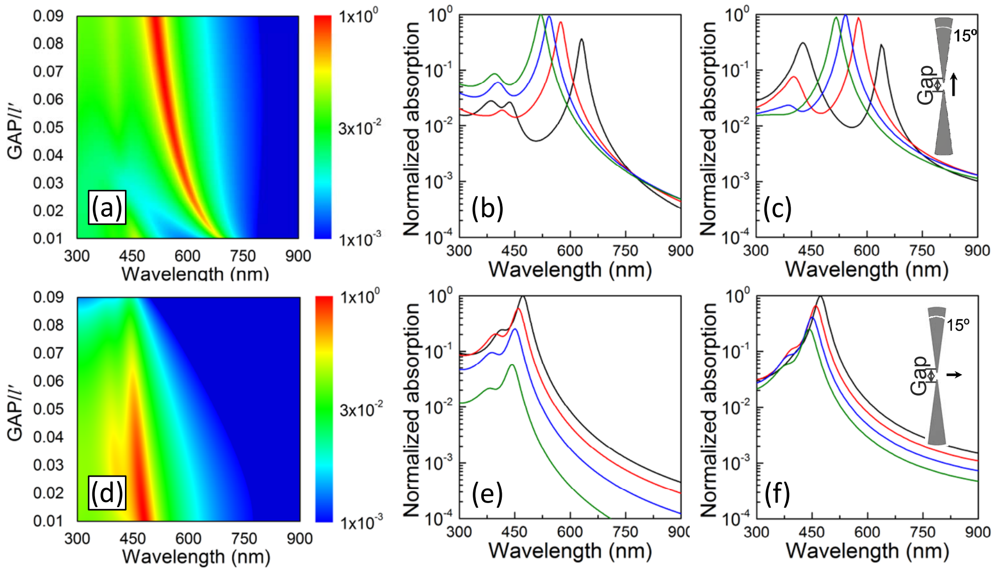

Fig. 2. Normalized absorption cross section as a function of gap size for a bowtie with 15 deg arm angle and illuminated by a vertical (top row) and horizontal (bottom row) dipole: analytical (a, b, d, e) and simulation (c, f) results.

REFERENCES

[1] K. E. Dorfman, P. K. Jha, D. V. Voronine, P. Genevet, F. Capasso, and M. O. Scully, "Quantum-coherence-enhanced surface plasmon amplification by stimulated emission of radiation," *Phys. Rev. Lett.*, vol. 111, no. July, pp. 1–5, 2013.
[2] S. Kühn, U. Håkanson, L. Rogobete, and V. Sandoghdar, "Enhancement of single-molecule fluorescence using a gold nanoparticle as an optical nanoantenna," *Phys. Rev. Lett.*, vol. 97, no. JULY, pp. 1–4, 2006.
[3] A. V Akimov et al., "Generation of single optical plasmons in metallic nanowires coupled to quantum dots," *Nature*, vol. 450, no. November, pp. 402–406, 2007.
[4] X. Lu, M. Rycenga, S. E. Skrabalak, B. Wiley, and Y. Xia, "Chemical synthesis of novel plasmonic nanoparticles," *Annu. Rev. Phys. Chem.*, vol. 60, pp. 167–192, 2009.
[5] A. Biswas, I. S. Bayer, A. S. Biris, T. Wang, E. Dervishi, and F. Faupel, "Advances in top-down and bottom-up surface nanofabrication: Techniques, applications & future prospects," *Adv. Colloid Interface Sci.*, vol. 170, no. 1–2, pp. 2–27, 2012.
[6] H. Fischer and O. J. F. Martin, "Engineering the optical response of plasmonic nanoantennas," *Opt. Express*, vol. 16, no. 12, pp. 9144–9154, 2008.
[7] A. Aubry, D. Y. Lei, A. I. Fernández-Domínguez, Y. Sonnefraud, S. A. Maier, and J. B. Pendry, "Plasmonic light-harvesting devices over the whole visible spectrum," *Nano Lett.*, vol. 10, no. 7, pp. 2574–2579, Jul. 2010.
[8] L. Xu and H. Chen, "Conformal transformation optics," *Nat. Photonics*, vol. 9, no. 1, pp. 15–23, 2015.
[9] Y. Luo, D. Y. Lei, S. A. Maier, and J. B. Pendry, "Transformation-optics description of plasmonic nanostructures containing blunt edges/corners: from symmetric to asymmetric edge rounding," *ACS Nano*, vol. 6, no. 7, pp. 6492–506, Jul. 2012.
[10] Y. Luo, D. Y. Lei, S. A. Maier, and J. B. Pendry, "Broadband Light Harvesting Nanostructures Robust to Edge Bluntness," *Phys. Rev. Lett.*, vol. 108, no. 2, p. 023901, Jan. 2012.
[11] R. Collin, *Field Theory of Guided Waves*, New York, USA: McGraw-Hill, 1960.
[12] K. C. Gupta, R. Garg, I. Bahl, and P. Bhartia, *Microstrip Lines and Slotlines*, Norwood, USA: Artech House, 1996.
[13] M. Navarro-Cia and S. A. Maier, "Broad-band near-infrared plasmonic nanoantennas for higher harmonic generation," *ACS Nano*, vol. 6, no. 4, pp. 3537–44, Apr. 2012.